



US Lattice Quantum Chromodynamics

QCD for Particle Physics

Andreas S. Kronfeld
Fermilab & IAS TU München

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Elementary Particle Physics

- The central theme is to explore the smallest distance scales for evidence of new particles, new interactions, new symmetries, and new structures:
 - direct production of new particles and measurements of their couplings—
 - the “BSM” lattice gauge theories of new particles;
 - observations of the cosmos, e.g., dark matter—
 - BSM to explain their nature; QCD to understand the signals;
 - precise measurements need precise calculations—
 - QCD calculations of relevant hadronic matrix element.

Anna

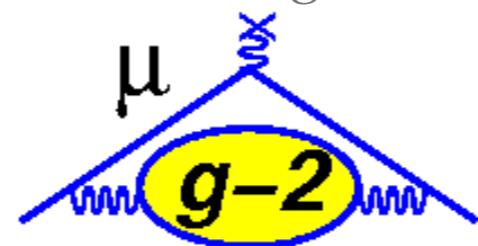
Andreas

QCD is Everywhere

parton distribution
functions



hadronic
muon $g-2$



decay & mixing
amplitudes



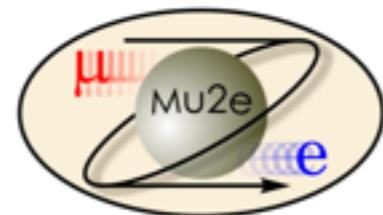
esoteric
hadrons:



dark-matter-nucleus
cross sections



muon-nucleus
cross sections



neutrino-nucleus
cross sections



USQCD Community Engagement

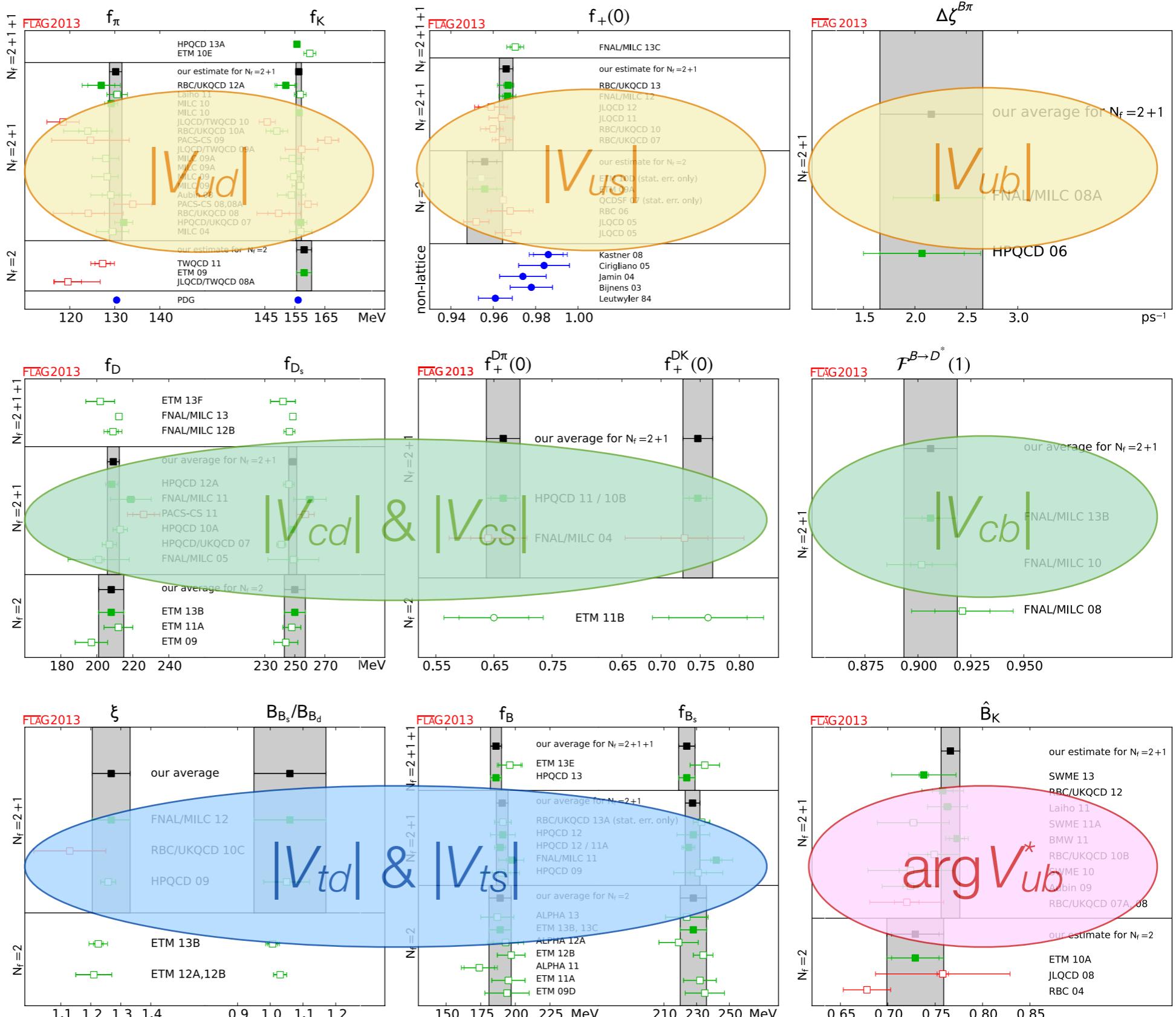
- 2013 HEP Community Planning (aka Snowmass):
 - participation in satellite meetings as well as Minneapolis;
 - reports: [Lattice](#), [Quark Flavor](#), [QCD](#), [Charged Leptons](#), [Higgs](#), [Computing](#).
- Particle Physics Project Prioritization Panel (P5):
 - (invited) presentations to P5 meetings;
 - USQCD focus evolved as P5 plan developed.
- Project X Physics Study: leadership role + lattice-QCD working group.

- Long-term interactions with *B*-factory community; recent examples:
 - BaBar/Belle legacy book (co-authors): [arXiv:1406.6311 \[hep-ex\]](https://arxiv.org/abs/1406.6311);
 - **Belle 2 Theory-interface Platform** (talks, WG conveners, Lattice Board, Advisory Board).
- Lattice Meets Experiment workshops (QCD): [2014](#), [2010](#), [2007](#), [2006](#).
- Programs/workshops at [INT](#), [KITP](#), [MITP](#), [Siegen](#),
- Invited talks at collaboration meetings, e.g., DUNE, g-2, ORKA, BES 3,
- Conference IAC memberships (partial list): CKM series, Charm series, Beauty series, Lepton-Photon 2015,

Lattice QCD and High Energy Physics

- Intensity Frontier:
 - B -meson, D -meson, and kaon matrix elements;
 - hadronic contributions to the muon magnetic moment ($g-2$);
 - nucleon matrix elements.
- Energy frontier—precision Higgs physics:
 - heavy quark masses and strong coupling α_s (from quark flavor program).
- Cosmic frontier:
 - matrix elements for dark matter detection.

Increments vs. steps



2013 Forecasts for Quark Flavor Physics

FLAG	Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2018 lattice error
🥇 🥈 🥉	f_K/f_π	$ V_{us} $	0.2%	0.5%	0.5%	0.15%
🥇 🥈	$f_+^{K\pi}(0)$	$ V_{us} $	0.2%	–	0.5%	0.2%
🥇 🥈	f_D	$ V_{cd} $	4.3%	5%	2%	< 1%
🥇 🥈	f_{D_s}	$ V_{cs} $	2.1%	5%	2%	< 1%
🥇 🥈	$D \rightarrow \pi \ell v$	$ V_{cd} $	2.6%	–	4.4%	2%
🥇 🥈	$D \rightarrow K \ell v$	$ V_{cs} $	1.1%	–	2.5%	1%
🥇 🥈	$B \rightarrow D^* \ell v$	$ V_{cb} $	1.3%	–	1.8%	< 1%
🥇 🥈	$B \rightarrow \pi \ell v$	$ V_{ub} $	4.1%	–	8.7%	2%
🥇 🥈 🥉	f_B	$ V_{ub} $	9%	–	2.5%	< 1%
🥇 🥈 🥉	ξ	$ V_{ts}/V_{td} $	0.4%	2–4%	4%	< 1%
🥇 🥈 🥉	ΔM_s	$ V_{ts}V_{tb} ^2$	0.24%	7–12%	11%	5%
🥈 🥉	B_K	$\text{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%	< 1%

- Best 2 or 3 USQCD results (by 2013) were either the best worldwide (🥇), not far behind (🥈), or lagged slightly (🥉). (My take on FLAG summaries.)

Outline

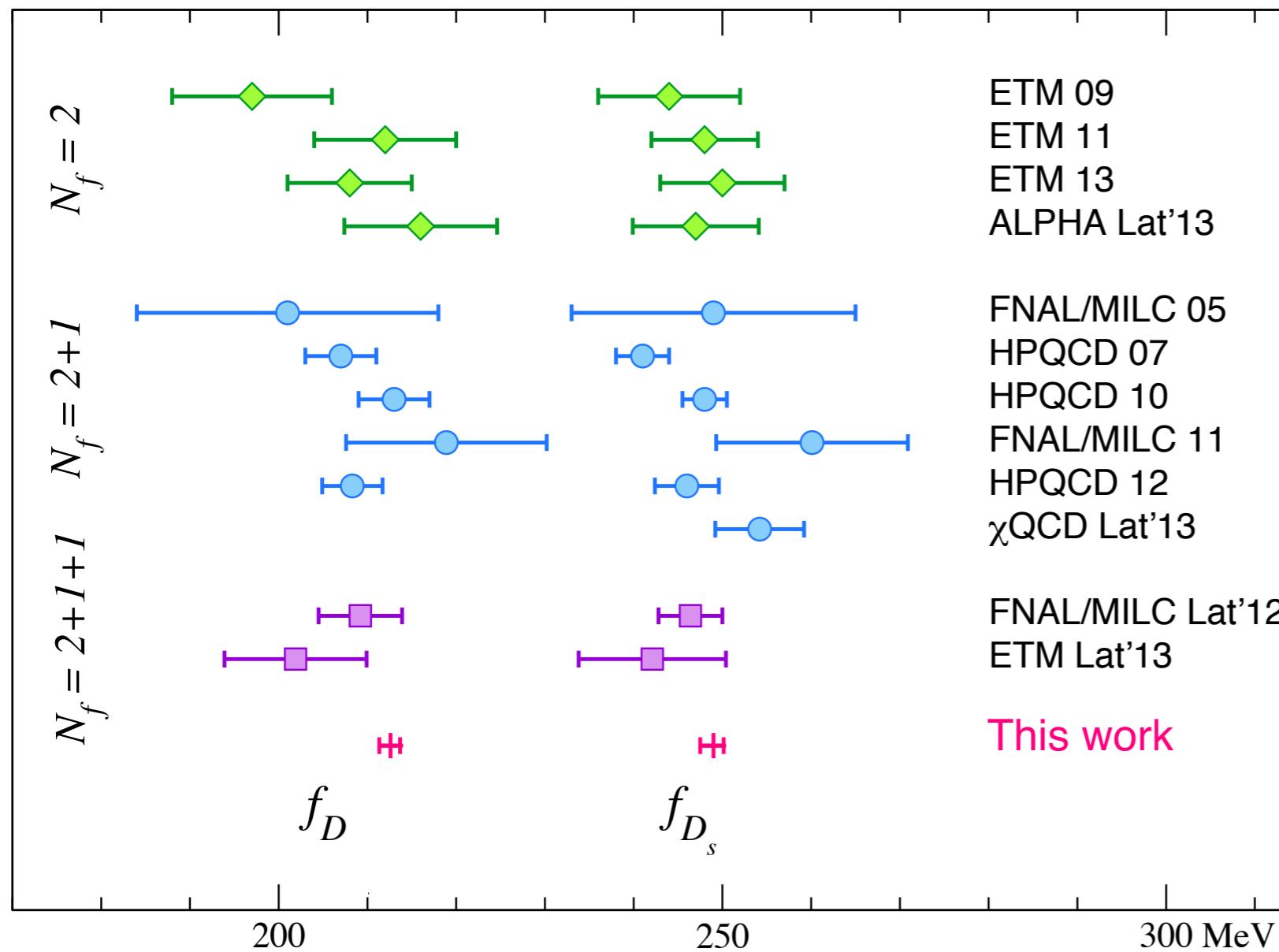
- Quark flavor highlights of the past year:
 - from the table: D -meson decay constants, semileptonic B decays
 - beyond the table: semileptonic Λ_b decays, kaon mass difference
- Other important highlights:
 - nucleon matrix elements for $\mu \rightarrow e$ conversion, dark matter, νN scattering
 - hadronic contributions to the muon's anomalous magnetic moment, $g-2$
- Outlook

Quark Flavor Physics

Charmed-Meson Decay Constants

Fermilab/MILC, *PRD* **90** (2014) 074509 [arXiv:1407.3772]

- First with light sea and valence directly at physical light quark mass.



- Other key features:
 - four lattice spacings;
 - large boxes;
 - 2+1+1 sea quarks.





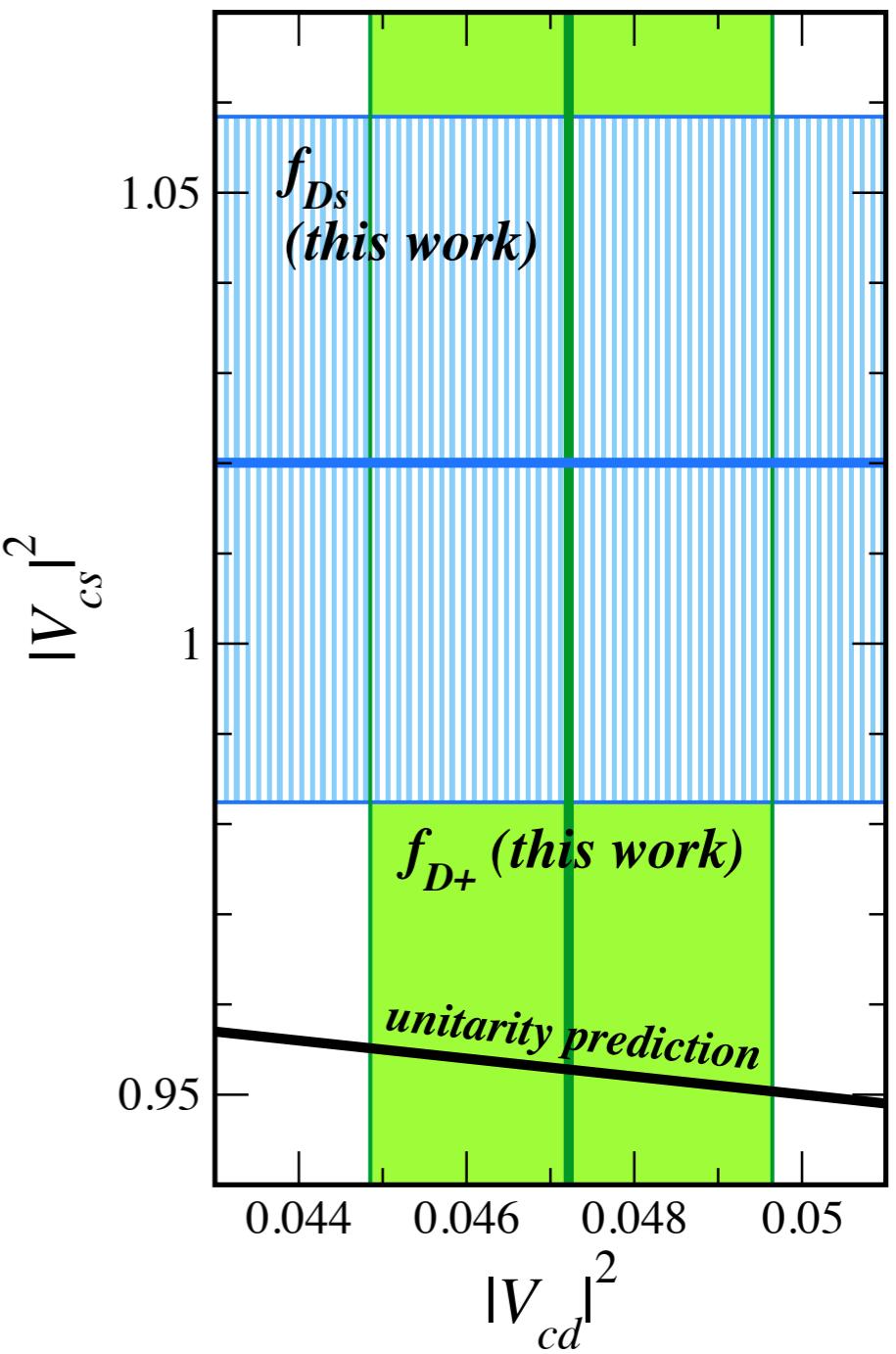
Determining $|V_{cd}|$ and $|V_{cs}|$

- Taking $f_{D^+}|V_{cd}|$ and $f_{D_s}|V_{cs}|$ from PDG:

$$|V_{cd}| = 0.217(05)_{\text{expt}}(1)_{\text{QCD}}(1)_{\text{QED}}$$

$$|V_{cs}| = 1.010(18)_{\text{expt}}(5)_{\text{QCD}}(6)_{\text{QED}}$$

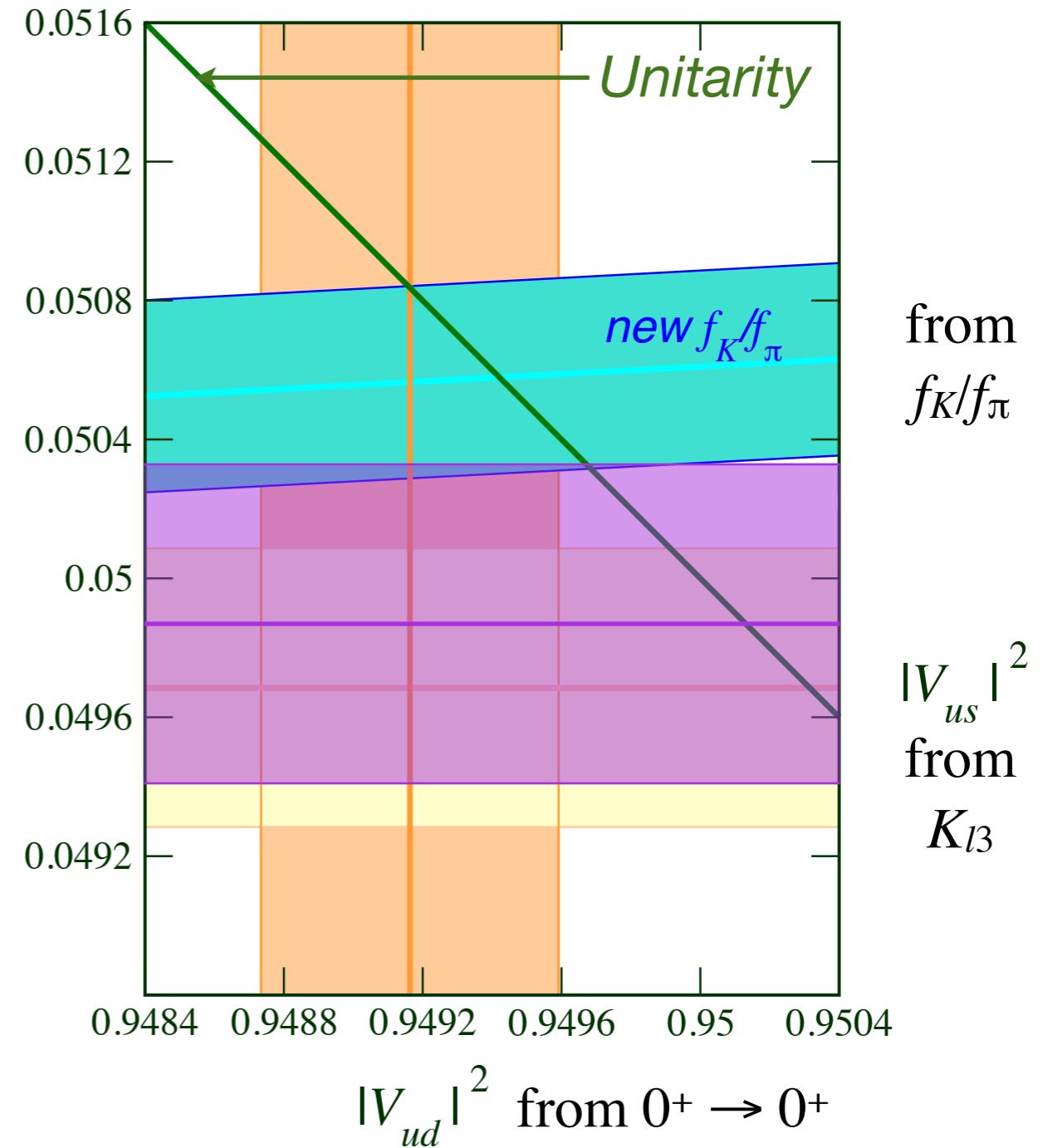
- The QCD uncertainty (0.5%) is now
 - smaller than that from experiment;
 - about the same as that from structure-dependent EM effects.
- Unitarity: $1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 = -0.07(4)$





First Row Unitarity Test: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1?$

- First results at physical point.
- $|V_{us}| = 0.2233(5)_{\text{expt}}(9)_{\text{QCD}}$
- $|V_{us}| = 0.2249(3)_{\text{expt}}(5)_{\text{QCD}}(5)_{|V_{ud}|}$
- [1]: arXiv:1312.1228 [FNAL/MILC]
- [2]: arXiv:1504.01692 [RBC/UKQCD]
- [3]: arXiv:1407.3772 [FNAL/MILC]
- $|V_{us}|^2$ now as precise as $|V_{ud}|^2$!
- $|V_{ud}| = 0.97425(22)$ (superallowed nuclear $0^+ \rightarrow 0^+$ β decay).

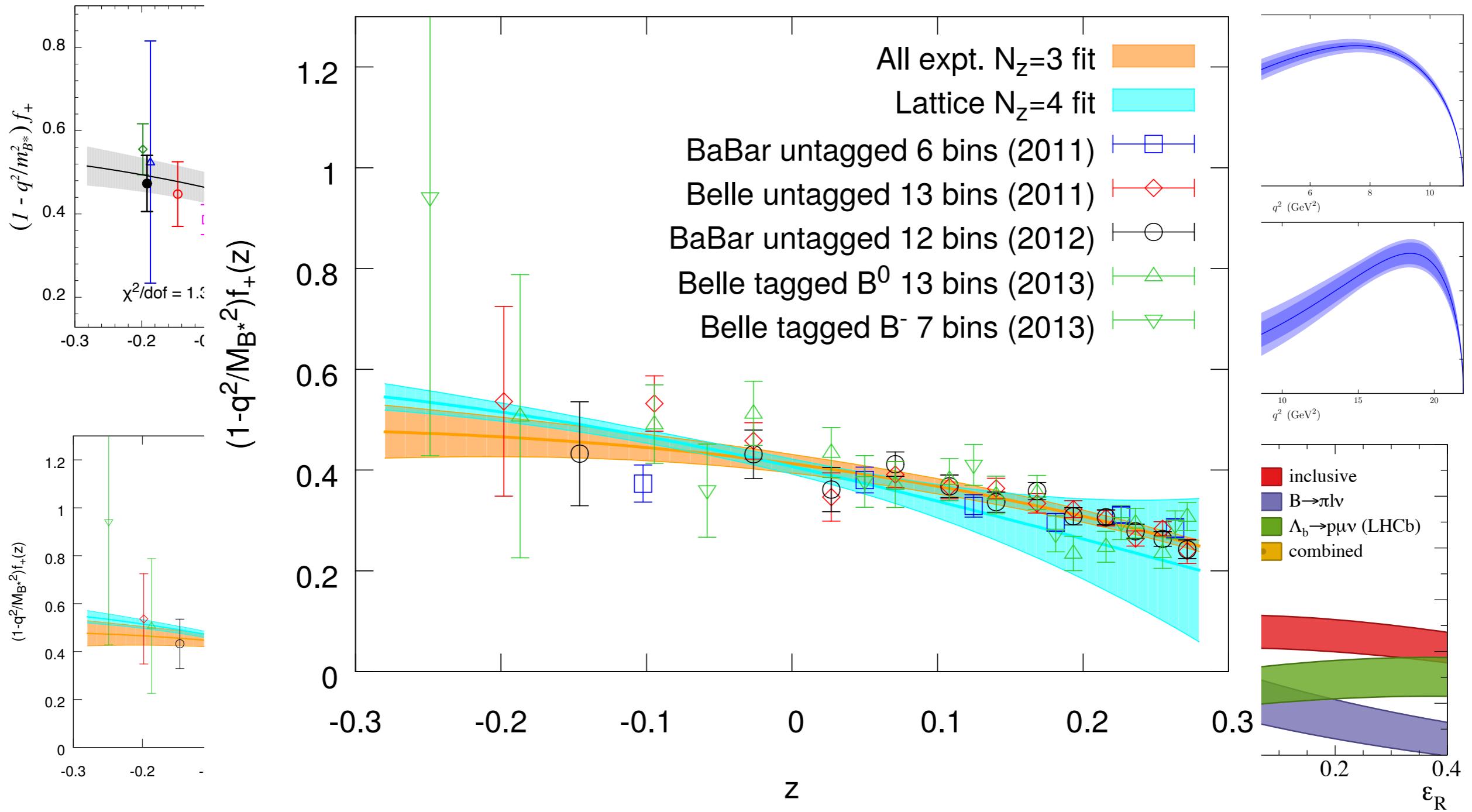


Semileptonic Decays in b Physics

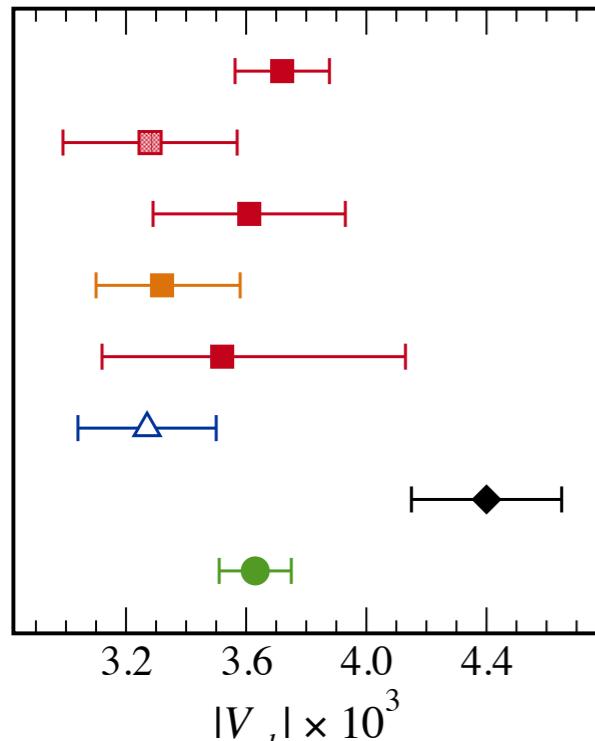
- A lot of activity in the past few months.
- $|V_{ub}|$ from $B \rightarrow \pi l \nu$, with z expansion to combine lattice QCD and experiment:
 - RBC/UKQCD [[arXiv:1501.05373](#)], Fermilab/MILC [[arXiv:1503.07839](#)].
- $|V_{cb}|$ from $B \rightarrow D l \nu$, over full kinematic range:
 - Fermilab/MILC [[arXiv:1503.07237](#)], HPQCD [[arXiv:1505.03925](#)].
- $|V_{ub}|/|V_{cb}|$ from $\Lambda_b \rightarrow p l \nu$ & $\Lambda_b \rightarrow \Lambda_c l \nu$, again with z over full kinematic range:
 - Detmold, Lehner, Meinel [[arXiv:1503.01421](#)] on RBC/UKQCD ensembles.



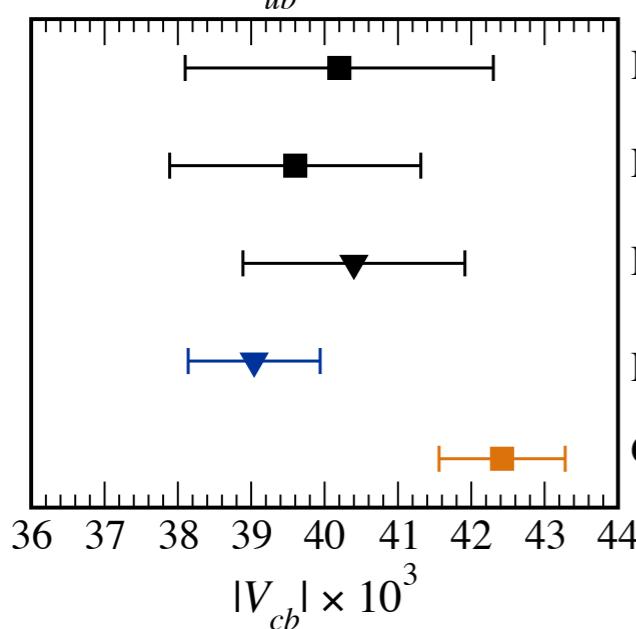
Combining Lattice QCD with Experiment



Comparisons of $|V_{ub}|$ & $|V_{cb}|$ Calculations



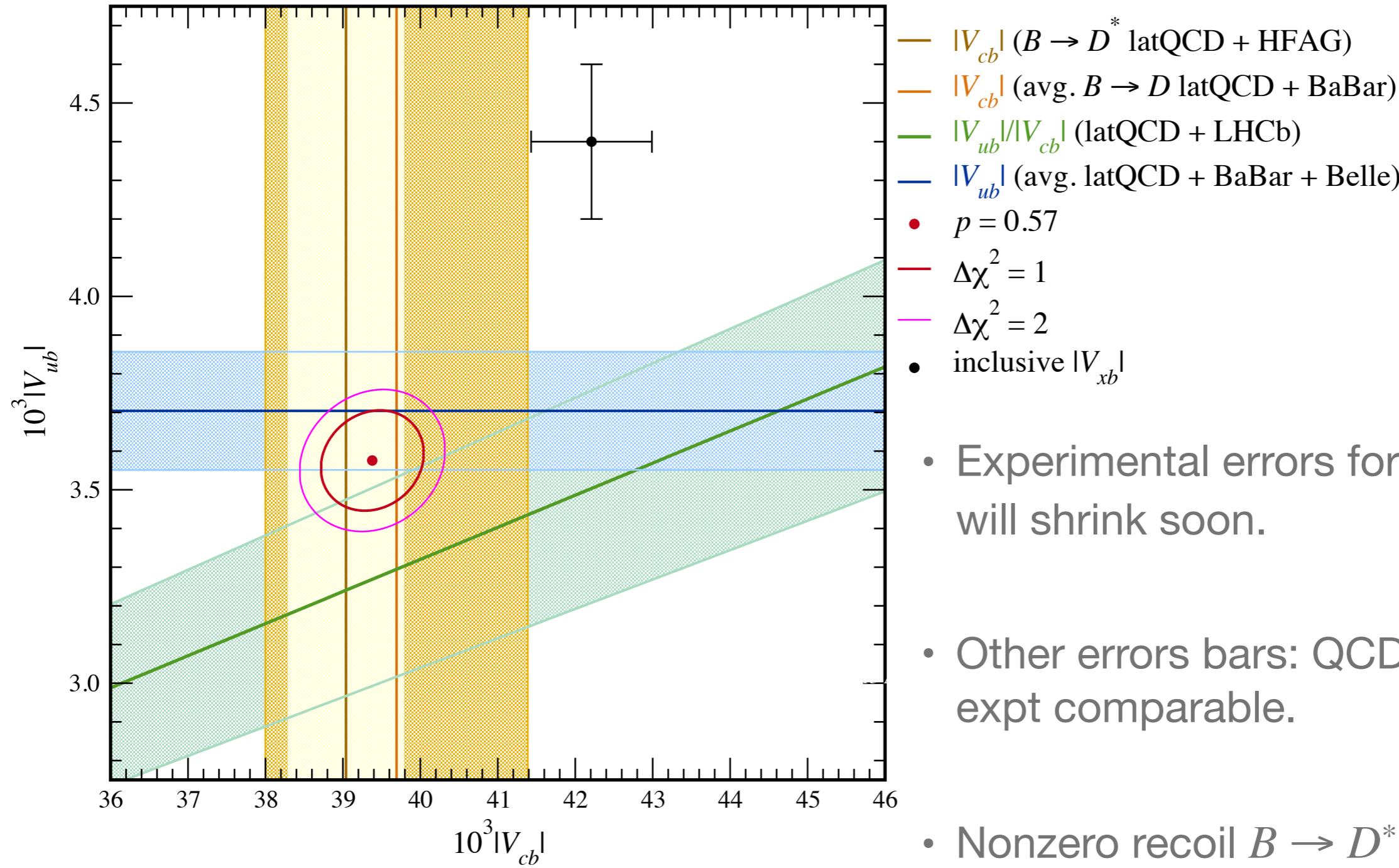
Fermilab/MILC 2015 + BaBar + Belle, $B \rightarrow \pi l \nu$
 Fermilab/MILC 2008 + HFAG 2014, $B \rightarrow \pi l \nu$
 RBC/UKQCD 2015 + BaBar + Belle, $B \rightarrow \pi l \nu$
 Imsong *et al.* 2014 + BaBar + Belle, $B \rightarrow \pi l \nu$
 HPQCD 2006 + HFAG 2014, $B \rightarrow \pi l \nu$
 Detmold *et al.* 2015 + LHCb 2015, $\Lambda_b \rightarrow p l \nu$
 BLNP 2004 + HFAG 2014, $B \rightarrow X_u l \nu$
 UTFit 2014, CKM unitarity



HPQCD '15 + BaBar '09, $B \rightarrow D, w \geq 1$
 Fermilab/MILC '15 + BaBar '09, $B \rightarrow D, w \geq 1$
 Fermilab/MILC '15 + HFAG '14, $B \rightarrow D, w = 1$
 Fermilab/MILC '14 + HFAG '14, $B \rightarrow D^*, w = 1$
 Gambino & Schwanda '13, $B \rightarrow X_c$ inclusive

- Consistency among lattice-QCD calculations:
- QCD sum rule $|V_{ub}|$ ✓;
- QCD sum rule $|V_{cb}|$ ✗.
- Tension with inclusive, in both cases.
- **Avidly discussed @ MITP: lattice, pheno, experiment.**

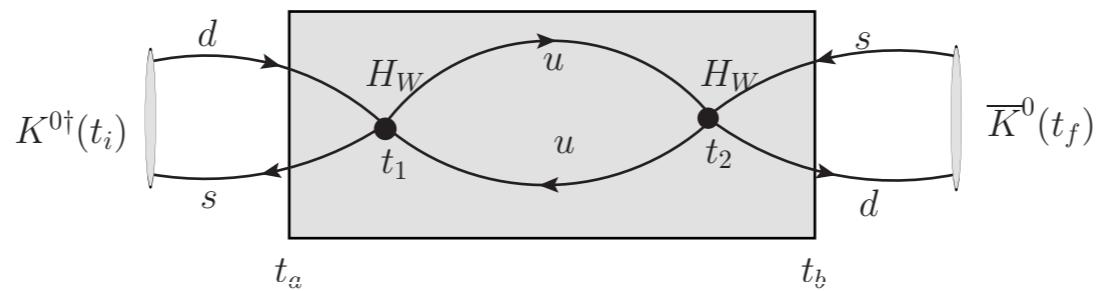
Synthesis of $|V_{ub}|$ & $|V_{cb}|$ Calculations



Kaon Mass Difference

RBC/UKQCD, *PRL* **113** (2014) 112003 [arXiv:1406.0916]

- First complete calculation in lattice QCD.
- 10% SM calculation would bound scale of new physics at $\Lambda > 10^4$ TeV.
- Technically challenging, with two insertions of the electroweak interaction,



so pushes scope of lattice QCD into a new class of processes.

- Result agrees with experiment, but errors are still large:

$$\Delta M_K = \begin{array}{ll} 3.19(41)(96) & \times 10^{-12} \text{ MeV} \\ 3.483(6) & \times 10^{-12} \text{ MeV} \end{array} \begin{array}{l} \text{lattice QCD} \\ \text{experiment} \end{array}$$



Nucleon Matrix Elements

Mu2e; LUX, CDMS, COUPP; SuperCDMS, LZ
MiniBooNE, SciBooNE, MicroBooNE
MINOS, MINERvA, NOvA
DUNE

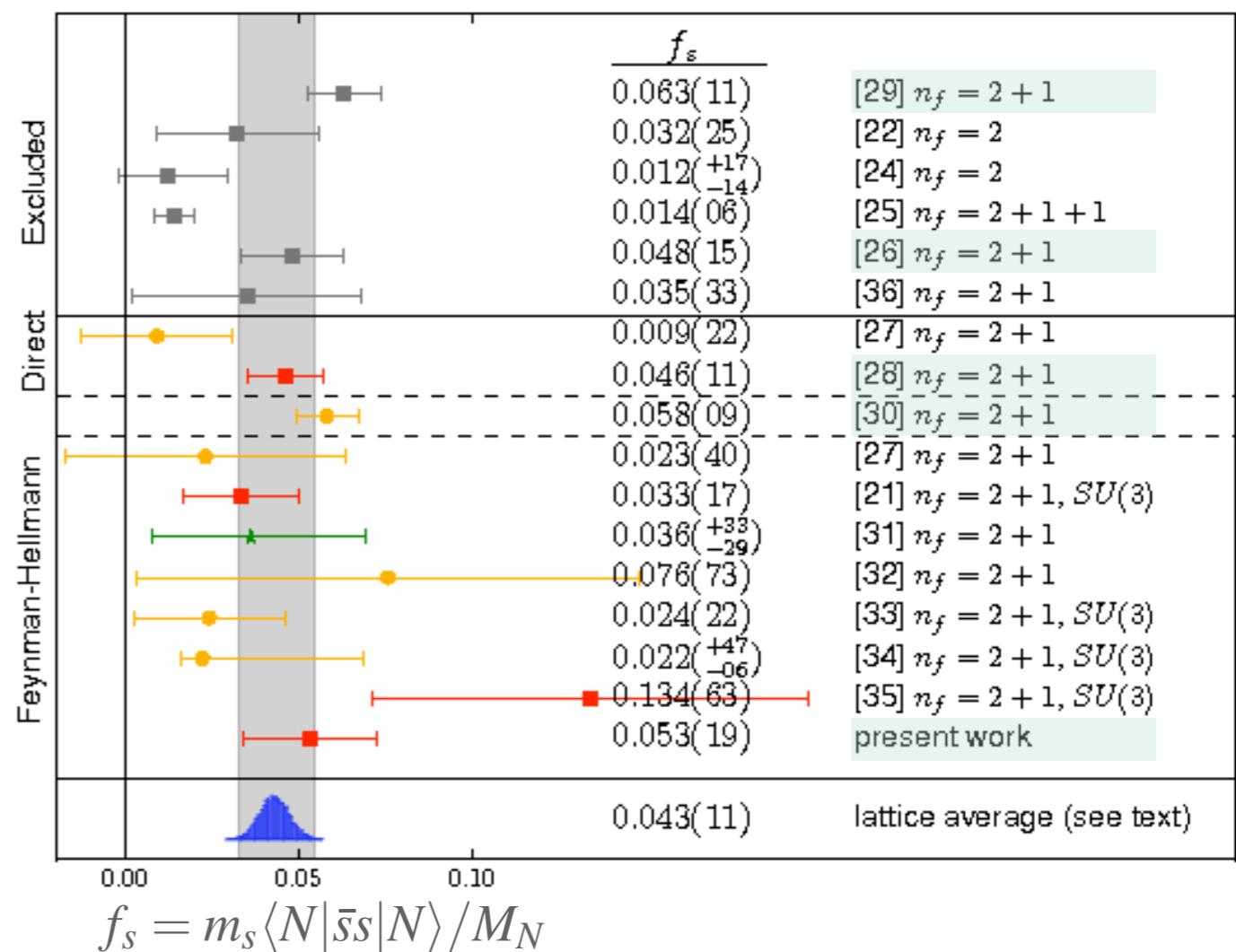
Charged-Lepton Flavor Violation

- Possible with SM+neutrino mixing, but so small it's unobservable.
- Mu2e: search for a muon converting to an electron in the field of a nucleus:
 - **significant signal = unambiguous evidence for a new force.**
- Spin structure of such interaction (obviously) unknown.
- Need nucleon matrix elements of vector, scalar, etc., densities.
- Vector matrix element known from electron scattering—therefore
 - **key targets** for lattice QCD: $m_s \langle N | \bar{s}s | N \rangle$, $\sigma_{\pi N} = \frac{1}{2}(m_u + m_d) \langle N | \bar{u}u + \bar{d}d | N \rangle$.

Model Discrimination in CLFV

- Many calculations underway.
- The same matrix elements are needed to interpret direct dark matter detection.
- Have refuted older estimates used in phenomenology.
- The compilation shows that errors & scatter are still large.
- Aiming for **10–20% errors**, to interpret any $\mu \rightarrow e$ signal.

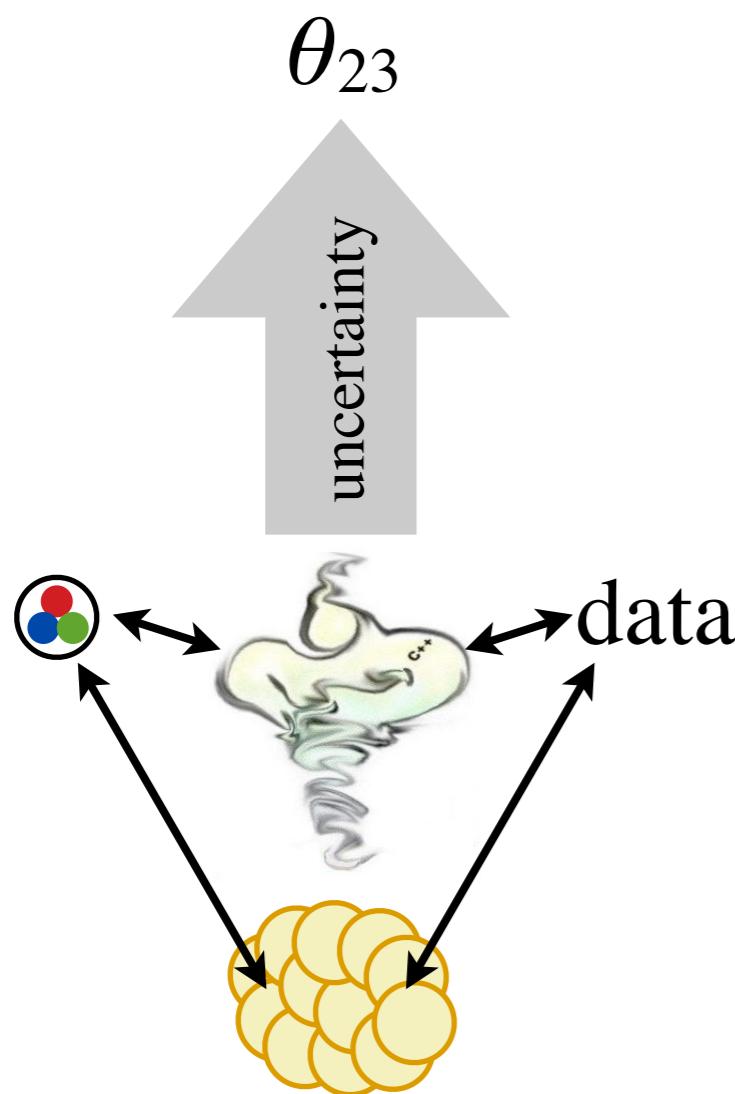
Junnarkar & Walker-Loud, arXiv:1301.1114



USQCD results highlighted.

Neutrino Experiments

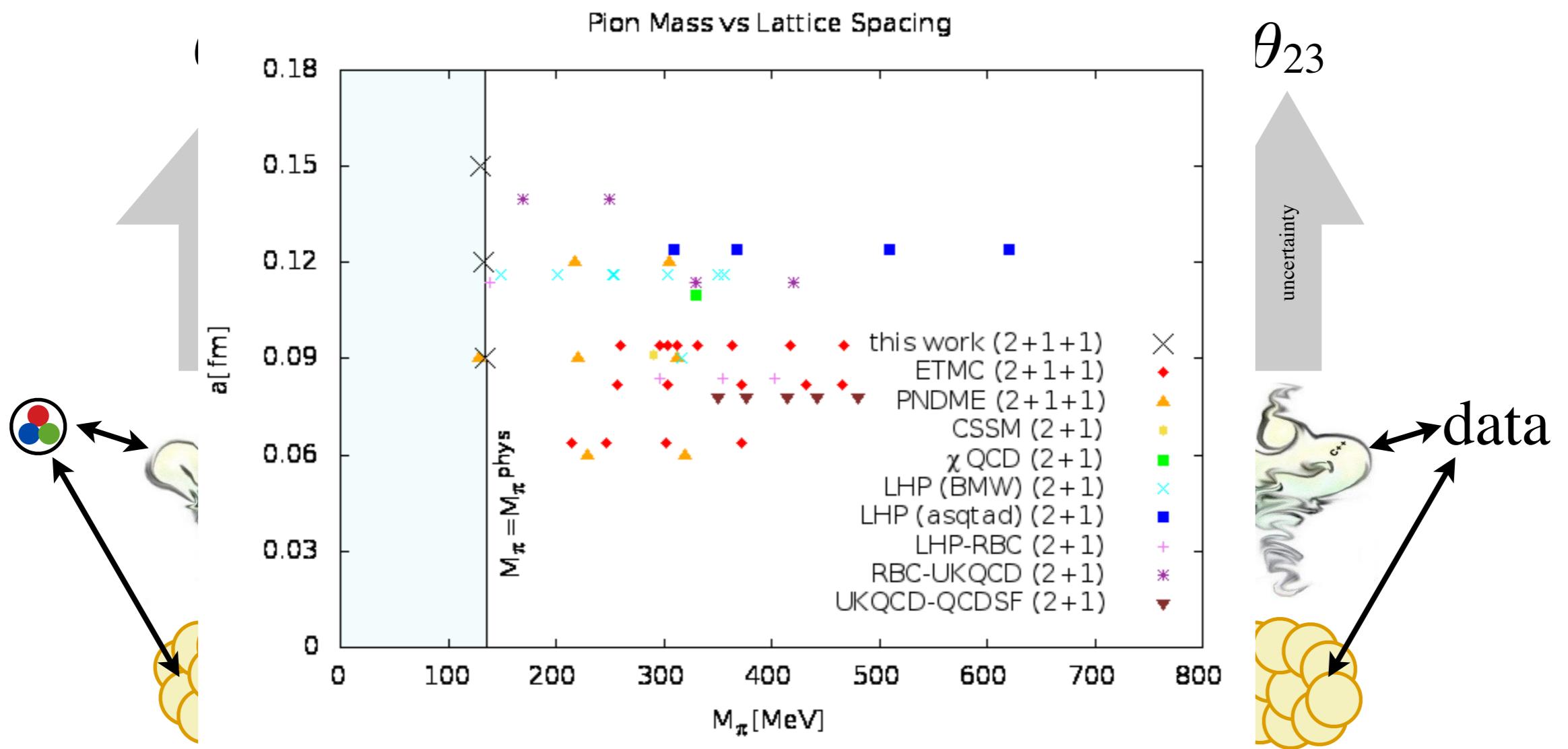
- Status: Ansatz for form factor, models for nucleus, **GENIE** to analyze:



- Experiments with different kinematic bite yield different results for dipole mass M_A .
- Within a single experiment (e.g., MINERvA), different measurements can favor/disfavor different nuclear models.
- Goals for oscillation measurements in DUNE will need better separation of nucleon and nuclear effects.
- Disruptive technology needed!

Vicious Cycle

- Disruptive technology: *ab initio* nucleon-level calculations from lattice QCD.



- Many lattice-QCD calculations: time to interface with neutrino physicists.

Other Nucleon Matrix Elements

- Further examples of matrix elements of interest to HEP and NP:
 - Scalar and tensor charges (similar to g_A in lattice QCD), probed by precise neutron decay experiments: **(ultra)cold neutrons at LANL, SNS.**
 - Baryon-number violation, probed in proton decay or neutron-antineutron oscillations: **DUNE** and proposed n - \tilde{n} experiments.
 - Electric dipole moments: a clear sign of CP violation: proton, neutron, and other systems, to disentangle strong CPV from BSM CPV: many expts, including ideas suited for **FRIB**.
 - USQCD efforts on all these fronts.

Muon Anomalous Magnetic Moment

Muon ($g-2$) aka Fermilab E989

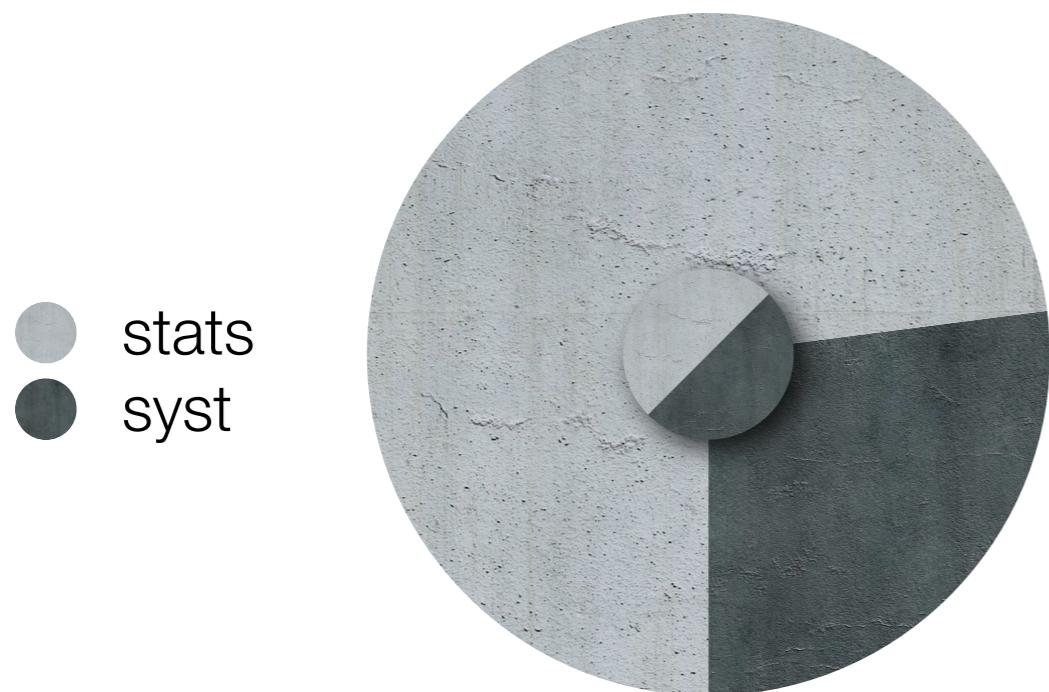
Muon ($g - 2$): Error Budgets

$$a = \mu \frac{2m}{e\hbar} - 1 = \frac{1}{2}(g - 2)$$

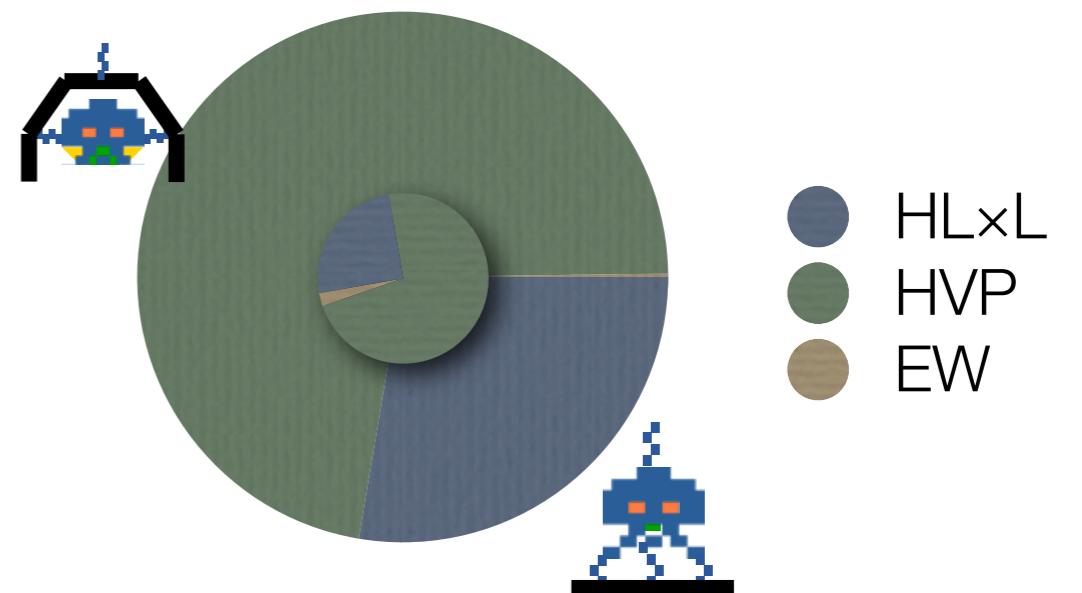
- Fermilab E989 is being mounted to confirm a well-known tension between BNL E821 & SM.

$$10^{11} a_\mu = \frac{116592089(63)}{116591802(49)} \text{ expt}$$

285(63)(49) is a huge difference

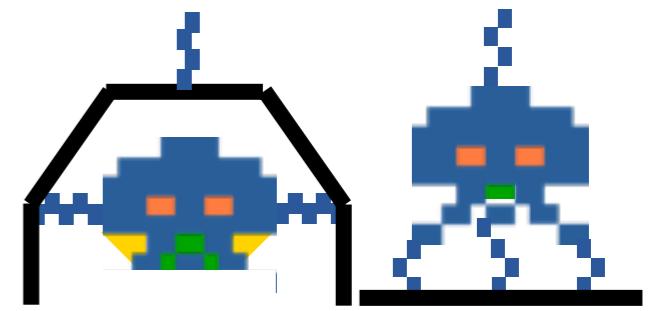


BNL E821 → FNAL E989

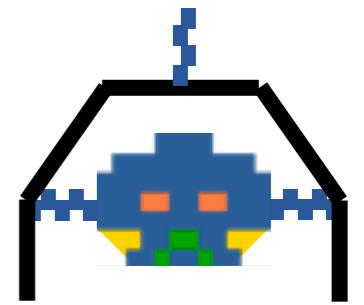


Standard Model
Calculation

Lattice QCD for $g-2$



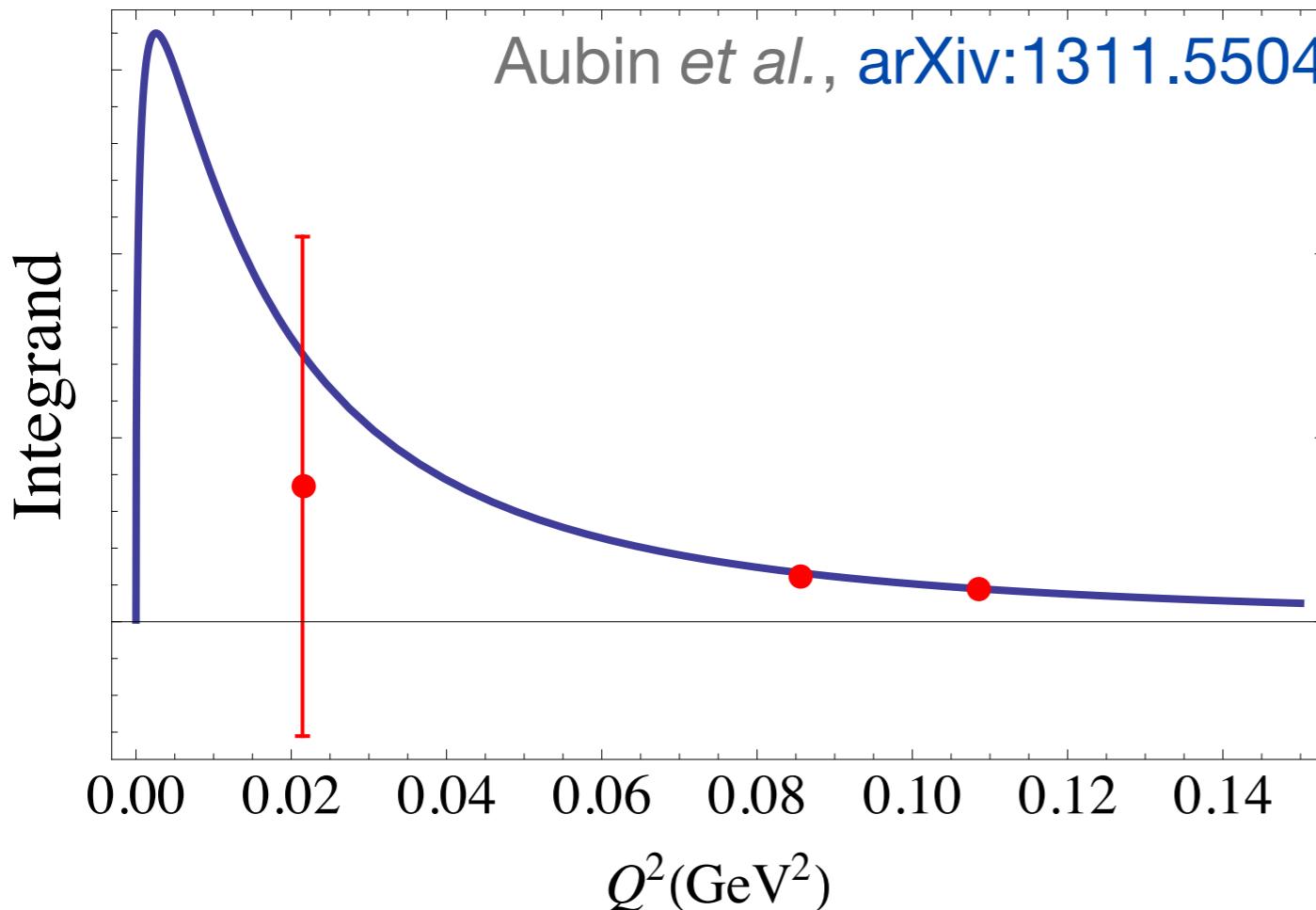
- With lattice QCD, one can compute $\text{FT}\langle V_\mu(x)V_\nu(0) \rangle$ or $\text{FT}\langle V_\mu(x)V_\nu(y)V_\rho(z)V_\sigma(0) \rangle$ (**from first principles**) and convolute the result with QED Feynman diagrams:
 - a challenging 2-point function;
 - a very ambitious set of 4-pt functions—or invent better ideas: see below.
- Long-term lattice-QCD goal is two numbers:
 - Hadronic vacuum polarization ($\text{HVP} \approx 7000 \times 10^{-11}$) to 0.2% and
 - Hadronic light-by-light ($\text{HL} \times \text{L} \approx 100 \times 10^{-11}$) to 5%—then
 - precision would then match goal of Fermilab E989.



HVP: Issues and Progress

- The key expression is [Blum, *PRL* **91** (2003) 052001 [[hep-lat/0212018](#)]]

$$a_\mu^{\text{HVP(LO)}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty f_{\text{QED}}(Q^2) [\Pi(Q^2) - \Pi(0)]_{\text{QCD}}, \quad \Pi \sim \text{FT} \langle V_\mu(x) V_\nu(0) \rangle$$



- Challenges:
 - control noise !!
 - for small $q^2 \sim m_\mu^2 \neq 0$!!!
 - addressed in turn on next two slides.

All Mode Averaging

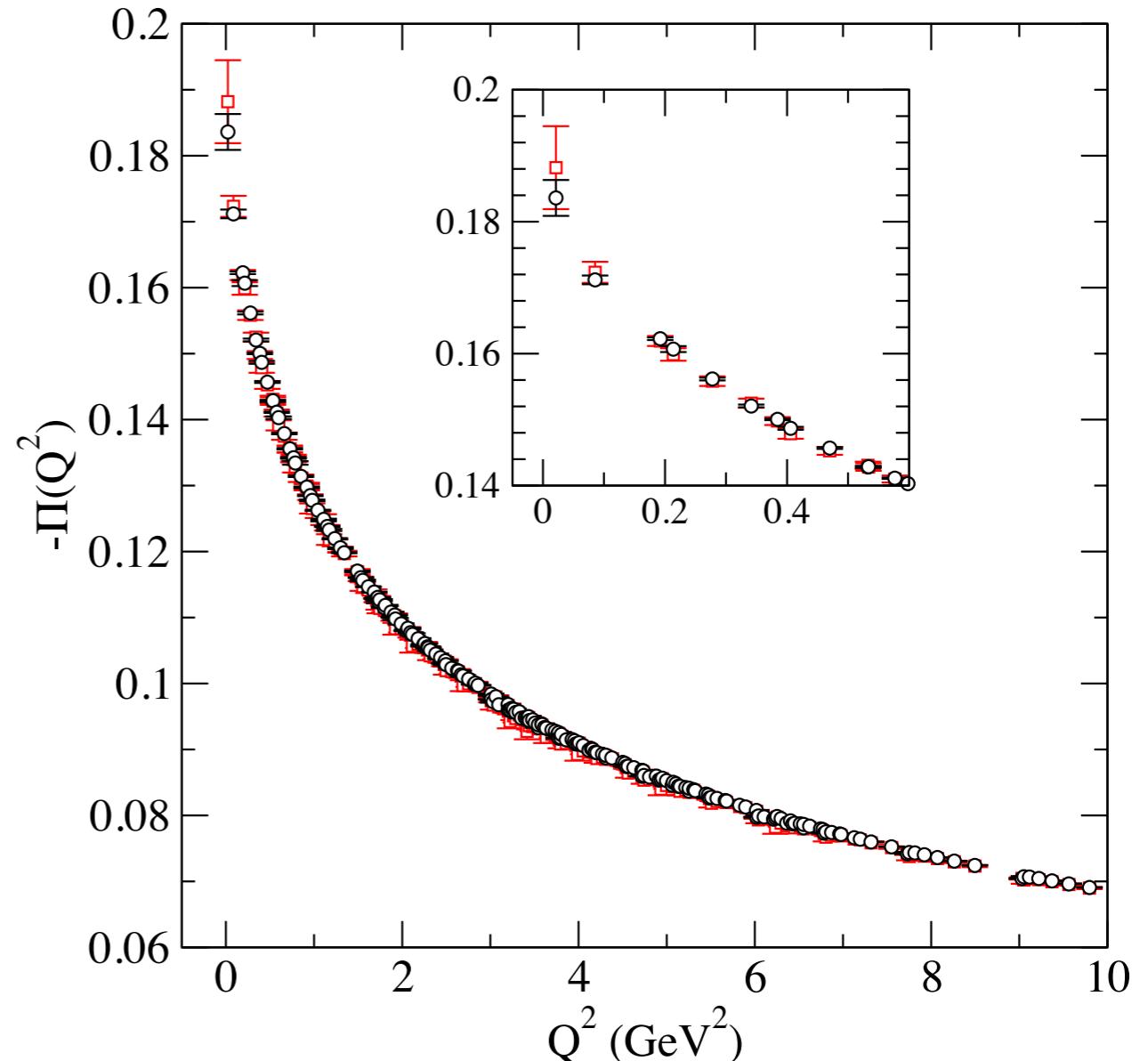
Blum, Izubuchi, Shintani, *PRD* **88** (2013) 094503 [[arXiv:1208.4349](https://arxiv.org/abs/1208.4349)]

- Member of a class of “covariant approximation averaging”.
- Key idea:

$$\mathcal{O}' = (\mathcal{O} - \tilde{\mathcal{O}}) + \frac{1}{N_G} \sum_{g=1}^{N_G} \tilde{\mathcal{O}}^g$$

where g is a symmetry.

- under averaging, $\tilde{\mathcal{O}}^{(g)}$ terms cancel, but variance can be much smaller;
- if $N_G \widetilde{\text{CPU}} < \frac{\text{noise}}{\text{noise}'} \text{CPU}$, then procedure is cost effective.

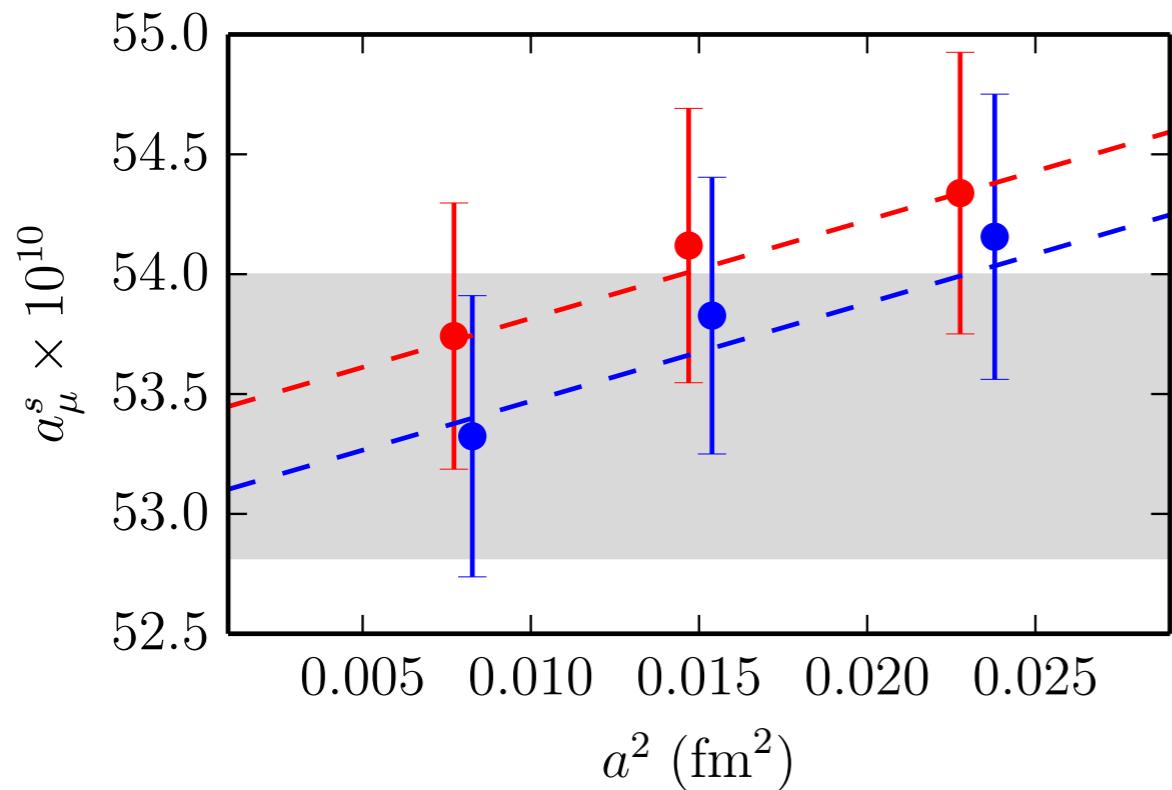


Broadly effective: [arXiv:1402.0244](https://arxiv.org/abs/1402.0244)

Time Moments

HPQCD, *PRD* **89** (2014) 114501 [[arXiv:1403.1778](https://arxiv.org/abs/1403.1778)]

- Exploits theorems relating Stieltjes integrals and Padé approximants, first explored for $g-2$ in Blum et al. [[arXiv:1205.3695](https://arxiv.org/abs/1205.3695)].
- Replace $\Pi(q^2)$ with its derivatives, which can be computed from a garden-variety correlation function: $\sum_t t^{2n} G(t) = (-1)^n \left. \frac{\partial}{\partial q^{2n}} q^2 \Pi(q^2) \right|_{q^2=0}$

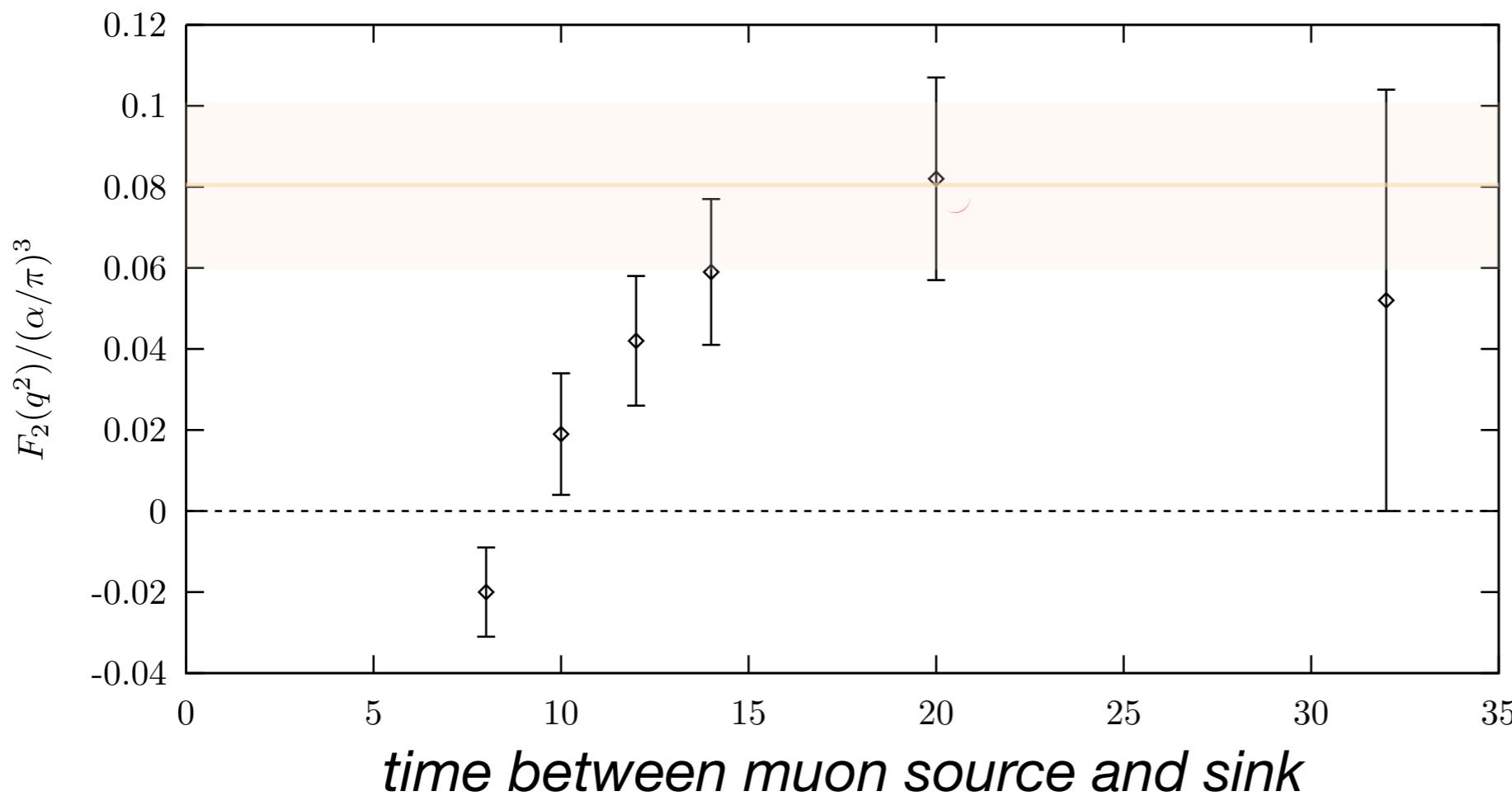


- Padé theorems \Leftarrow convergence.
- So far, available only for a_μ from strange, charm, and bottom quarks.
- Complementary to other methods, e.g., twisted boundary conditions.

First Calculation of $\text{HL} \times \text{L}$ in Lattice QCD

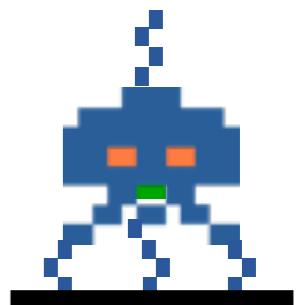
Blum, Chowdhury, Hayakawa, & Izubuchi, *PRL* **114** (2015) 012001 [arXiv:1407.2923]

- Lattice gauge theory of QCD **and** QED—put one photon in by hand:

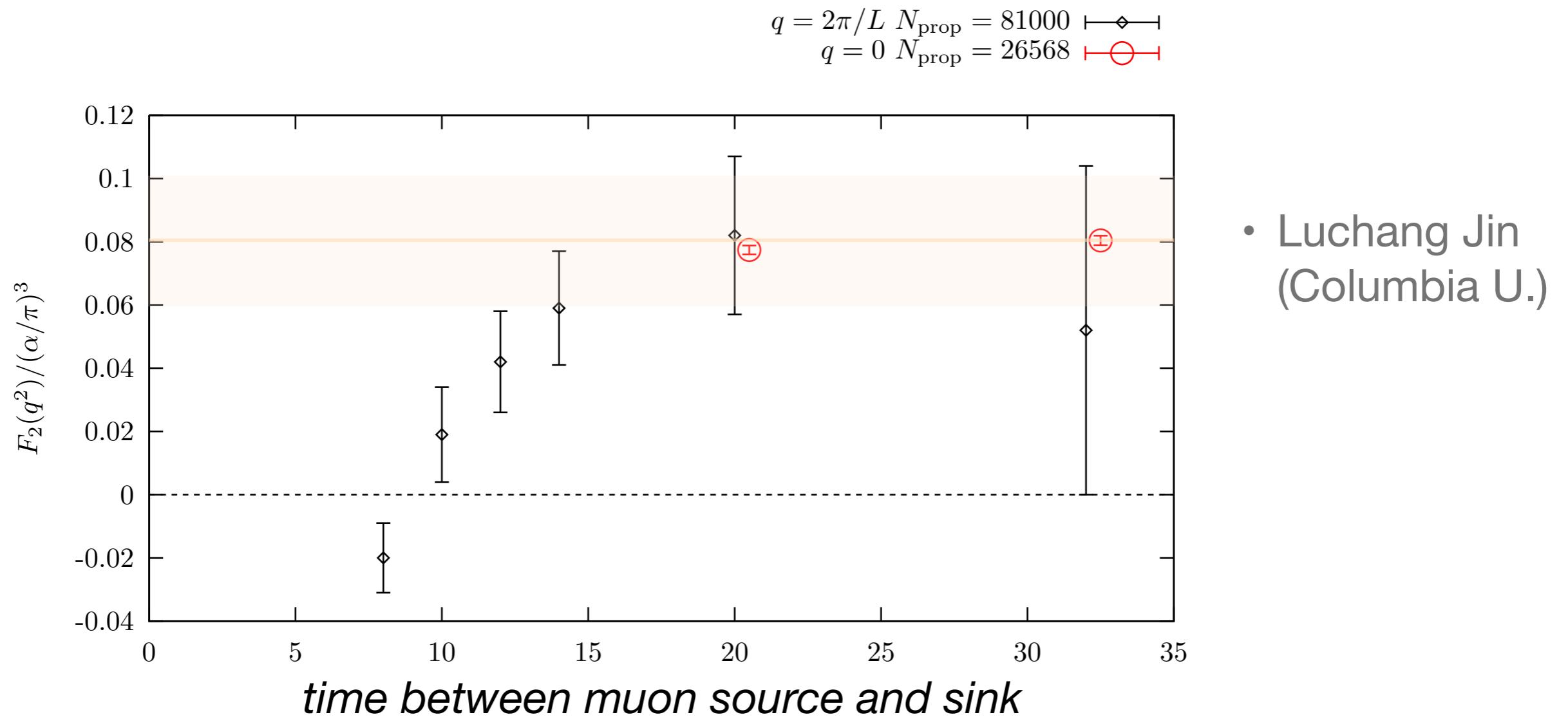


- Large excitation-state contribution ($\mu\gamma$ state).

- Agreement with pheno fortuitous:
 - depends on q^2 and masses:
 - $m_\mu = 175 \text{ MeV}$,
 $m_\pi = 333 \text{ MeV}$



- Dramatic recent improvement with stochastic method for photon.
- At same cost, much smaller error bars **and** even at (the desired) $q^2 = 0$.



- New space for future work: optimize strategy for treating each photon.

Conclusions

Quark Flavor Physics

- USQCD provides the computing resources for the world-leading efforts in quark flavor physics: Fermilab/MILC, HPQCD, RBC/UKQCD.
- Many outstanding results omitted in this talk (all world-leading):
 - heavy quark masses (HPQCD);
 - strong coupling α_s (HPQCD);
 - flavor-changing neutral currents (Fermilab/MILC, HPQCD);
 - leptonic B decays & $B^0-\bar{B}^0$ mixing (Fermilab/MILC, HPQCD, RBC/UKQCD).
 - amplitudes for $K \rightarrow \pi\pi$ processes (RBC/UKQCD).

Nucleon Matrix Elements

- Worldwide effort in “cold nuclear lattice QCD”.
- Several specific examples becoming very relevant to HEP:
 - scalar matrix elements for dark matter detection and $\mu \rightarrow e$ conversion;
 - nucleon axial form factor for neutrino physics.
- USQCD has HEP and NP components:
 - demonstrated ability to connect to experimentalists;
 - potential to foster collaborations among several communities.

Muon Magnetic Moment

- Lattice-QCD techniques pioneered under auspices of USQCD.
- Innovation abounds:
 - new ideas for a_μ^{HVP} , which makes feasible a %-level lattice-QCD calculation of within the next few years;
 - new ideas for $a_\mu^{\text{HL}\times\text{L}}$, which are turning lattice QCD from the only possibility to a genuine possibility.
- Coming experiment + sufficient computing \Rightarrow ideas.
- Algorithmic ideas (e.g., all-mode averaging) have broad application.

USQCD is Everywhere

- Excellent record of achievement in quark-flavor physics:
 - at least 11 PRLs in HEP since 2010 with USQCD participation, with over 300 citations;
 - over 40 papers posted since last hardware review;
- New opportunities more widespread and more essential.

Backups

List of 2014/2015 Projects (QCD for HEP)

- Quark flavor physics:
 - DeTar: Quarkonium Physics: $X(3872)$ and $Z_c(3900)$
 - Ishikawa: High precision calculation of neutral B meson mixing with ...
 - Kelly: Lattice Determination of the $\Delta I = 1/2$, $K \rightarrow \pi\pi$ Amplitude
 - Mackenzie: Flavor Physics from B , D , and K Mesons on the 2+1+1 ...
 - Shigemitsu: High-Precision Heavy-Quark Physics
 - Witzel: B -meson physics: physical mass domain-wall light quarks and ...

- Muon magnetic moment:
 - Aubin: Hadronic contributions to the muon g-2 using staggered fermions
 - Izubuchi: Hadronic vacuum polarization and hadronic light-by-light ...
- Nucleon Matrix Elements
 - Lin: Probing TeV Physics through Neutron-Decay Matrix Elements
 - Soni: Improved calculation of proton decay matrix elements
- Configuration generation:
 - Sugar: QCD with Four Flavors of Highly Improved Staggered Quarks
 - Mawhinney: Production and Basic Measurements on 2+1+1 flavor ...